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Entitled: "PLANETARY NEBULAR CABON-TO-OXYGEN RATIOS, MORPHOLOGY AND EVOLUTION"

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Our program has consisted of two (2) endeavors: 1) collaboration with W.A. Feibelman on studies of high-excitation planetary nebulae, and 2) collaboration with S.P. Maran, T.P. Stecher, T.R. Gull, and others in studies of planetaries in the Magellanic Clouds and one in the Fornax Galaxy.

High-Excitation Planetary Nebulae

The general procedure is to combine observations secured with the image tube scanner (ITS) at the Shane 3m telescope with data obtained with the International Ultraviolet Explores, IUE. The importance of IUE studies for abundance determinations is well illustrated for NGC 6741 (Aller _et al_. 1983). Let us first, however, discuss NGC 6537 per Feibelman _et al_. (1985).

We have analyzed the spectrum of this nitrogen-rich object with the aid of the theoretical nebular models. The models permit one to estimate the fraction of unobservable ions of abundant elements. On the scale log N(H) = 12, the logarithmic abundance values for He, C, N, and O are as follows:

	He	C	N	O
NGC 6537	11.27	7.6	8.95	8.23
Sun	11.0	8.66	7.98	8.91

The abundances of Ne, S, Cℓ, and Ar appear to be essentially solar to within a factor of two. Our interpretation is that the progenitor of NGC 6537 had a chemical composition not differing greatly from that of the Sun. In the course of its prenebular evolution, C and probably O were converted to N and much H was converted to helium.

Most planetaries show enhanced carbon and some show enhanced nitrogen with respect to the Sun. NGC 6537 resembles NGC 6302 in showing a depletion of carbon and an enhancement of nitrogen, but NGC 6302 has about the same O abundance as the average planetary. The depletion of carbon in NGC 6537 is more severe. Thus, NGC 6537 appears to be a unique object in whose progenitor star the carbon-nitrogen and related cycles ran very efficiently converting not only carbon into nitrogen but evidently cutting into the oxygen supply as well: $p + {}^{16}O \rightarrow {}^{17}O$; $p + {}^{17}O \rightarrow {}^{14}N + \alpha$, but a temperature of 30,000,000 or more would be needed in the H-burning zone. Hence, a progenitor somewhat more massive than for an ordinary planetary is needed. The sum of the masses of C, N, and O in NGC 6537 differs from the corresponding solar value by about 25%, strongly suggesting that an original essentially solar abundance pattern may have been modified by nuclear reactions.

Two more remarkable high-excitation planetary nebulae are IC 1297 and M1-1. We have analyzed the spectra of these objects with the aid of the theoretical nebular models as far as possible. The models permit one to estimate the fraction of unobservable ions of abundant elements.

For IC 1297 we used Kudritzki's stellar flux model (Astron. Ap., 134, 139, 1984) for T = 85,000°K, log g = 4.72. The radius of the star is taken as 0.50 solar radii and the distance of the nebula is given as 5100 pc. We assume a thin shell of constant density 3000 atoms/cm^3, an inner radius of 0.17 parsecs and an outer radius of 0.204 parsecs. The inner zone is assumed to have a constant low density $N_\varepsilon = 12/cm^3$. The most remarkable feature of the spectrum of of IC 1297 is the great strength of the dielectronic recombination of λ1371 O V line. Although this line is seen as a P Cygni feature in a number of planetaries, it is always associated with a strong continuum and other easily recognized features of stellar origin. No star is visible on CCD images. Another curious feature of the spectrum is the great weakness of the ultraviolet nitrogen lines. The N abundance estimated from the [N II] lines by the usual methods predicts a much higher N abundance.

Abundances derived directly from the model and by using the model only to obtain ionization correction factors are in good agreement, generally. There is a large discordance for sulfur where we cannot represnt lines of both [S II] and [S III] simultaneously. On the scale log N(H) = 12, the logarithmic abundance values for He, C, N, O, Nℓ, S, Cℓ, and Ar are as follows:

	M1-1	IC 1297	Sun		M1-1	IC 1297	Sun
He	11.02	11.06	11.0	Ne	7.95	8.16	8.05
C	8.57	8.60	8.66	S	6.6	7.0	7.23
N	8.4	8.1	7.98	Cℓ	——	5.4	5.5:
O	8.7	8.74	8.91	Ar	6.32	7.2	6.57

M1-1 is one of the highest excitation planetary nebulae known. Large fractions of abundant elements such as C, N, O, S, and Ar must exist in unobservable ionization stages. Many trials were made in an effort to a satisfactory theoretical model, but none were successful, even though black bodies with T_{eff} as high as 225,000°K were used. Hence, it is difficult to establish chemical abundances.

Neither of these objects shows an excessive He abundance. The carbon abundances seem to be very nearly solar, but the nitrogen abundances are higher. Oxygen shows the usual depletion by about a factor of 1.6. Probably Ne is close to the solar abundance. Sulfur is poorly determined; it may not differ significantly from the solar value. Argon appears to be more abundant in IC 1297 than in the Sun.

NGC 6644 and NGC 6563 are two planetary nebulae of moderately high excitation (Aller, Keyes, and Feibelman 1987); we calculated theoretical nebular models using stellar fluxes given by Husfeld _et al_. (1984, _Astron. Ap._, _134_, 139) for $T(^*) = 85{,}000$ K, log g = 4.72, and obtained elemental abundances by fitting theoretical to observed line intensities and also by using the model to determine ionization correction factors to be applied to observed ionic concentrations. The abundances as compared with the sun are as follows:

NGC	He	C	N	O	Ne	S	Cℓ	Ar
6565	11.03	8.83	8.77	8.77	8.15	7.00	5.23	6.48
6644	11.07	9.01	7.96	8.47	7.75	6.58	4.86	6.0
Sun	11.0:	8.66	7.98	8.91	8.05	7.23	5.5	6.57

Although C appears to be about 1.5 times as abundant in NGC 6644 as it is in NGC 6565, N, O, Ne, S, Cℓ, and Ar are depleted by factors ranging from 2 to 6 in NGC 6644 as compared to NGC 6565. The high-velocity object, NGC 6644, was evidently made from a less metal-rich mixture than the Sun.

Temperatures of central stars of planetary nebulae are usually obtained by some variation of the Zanstra method or by an energy balance method. By this latter method, Preite-Martinez and Pottasch (1984) acquired temperatures for NGC 6565 in the neighborhood of 53,000 K, while Reay _et al_. (1984) find

Zanstra temperatures of 185,000 and 130,000 for H I and He II. Such high central star temperatures cannot be in any way reconciled with the absence of [Ne V] in NGC 6565. For this nebula, Kohoutek and Martin (1983) find H and He II Zanstra temperatures of 69,000 and 87,000 to be more consistent with the level of excitation of the nebula, which seems to fit $T(^*) = 85,000$ K. For NGC 6644 the energy balance method gives a temperture of about 85,000, and Zanstra temperatures in excess of 70,000 and 95,000 for H and He II, respectively. The severe discrepancies for NGC 6565 deserve further examination.

The bulk of our efforts has been spent on the interpretation of IUE data obtained on 12 Magellanic Cloud Planetaries in collaboration with T.R. Gull, S.P. Maran, T.P. Stecher, and A.G. Michalitsianos of NASA Goddard Space Flight Center. (For an account of earlier work, see Maran et al. 1982, Ap. J. Letters, 253, L43.) C.D. Keyes and L.H. Aller have developed refined theoretical models for six Large Magellanic Cloud (LMC) objects, P2, P7, P9, P25, P33, and P40 (Westerlund-Smith notation) and six Small Magellanic Cloud (SMC) objects (Henize notation). The improvements were possible largely because of better electron density data supplied by Michael Barlow in advance of publication, and the replacement of uniform density models by more realistic shell models. Another important improvement was the employment of a grid of recently published non-LTE model stellar atmospheres by Kudritzski and associates (Husfield et al. 1984) in place of model atmospheres calculated for every few combinations of T_{eff} and log g. These newer model atmospheres appear to describe more accurately the emergent flux distributions of central stars shortward of the Lyman limit.

One seemingly startling consequence of the use of the Kudritzski-type atmospheres, particularly, was the change in the required radii and attendant masses of the planetary nebulae nuclei (PNN). A previous investigation (Stecher et al. 1982, Ap. J. Letters, 262, L41) for the central stars of three planetaries suggested masses of the order of one solar mass. The more recent work indicates that the PNN masses fall in the range from 0.55 to 0.70 solar masses, a result more nearly in harmony with current theoretical expectations (Schönberner, D., and Weidemann, V., 1981, in Physical Processes in Red Giants, ed. I. Iben and R. Renzini (Dordrecht: Reidel), p. 463.

Tables 1 and 2 give the abundances of elements observed in the SMC and LMC, respectively. We compare the logarithmic abundances and C/O and N/O ratios with results from Magellanic Cloud H II regions, the mean for galactic planetaries, and the Sun (cf. Aller 1984, Physics of Thermal Gaseous Nebulae (Dordrecht: Reidel), p. ???. These results indicate that in the precursor stars of some of the nebulae, oxygen was probably destroyed by nuclear reactions. Even if those nebulae are excluded, however, it appears that the initial composition of many of the precursor stars of the Magellanic Cloud planetaries was depleted in oxygen to an extent significantly greater than in the corresponding objects in our Galaxy. The precursor stars of the Magellanic Cloud planetaries also probably were not massive enough to synthesize neon, sulfur, or argon, which are apparently deficient by factors of four (LMC) or five (SMC) with respect to their abundances in the Sun. The results obtained to date are being published in The Astrophysical Journal.

TABLE 1

Adopted Logarithmic Elemental Abundances and Ratios in the

Small Magellanic Cloud on Scale log N(H) = 12.00

	SMC						SMC H II Regions	Solar	Mean PN
	N2	N5	N43	N44	N54	N67			
He	11.05	11.09	11.05	11.03	11.03	11.17	10.92	11.00	11.00
C	8.74	8.90	8.52	8.40	8.69	6.27	7.16	8.67	8.71
N	7.5	7.17	7.62	7.50	7.10	7.47:	6.53	7.99	8.26
O	8.16	8.27	8.06	8.24	8.00	7.15	8.07	8.92	8.65
Ne	7.38	7.74	7.22	7.58	7.00	6.54	7.48	8.05	8.00
S	6.26	6.71	6.33	6.54	6.55	6.23	6.48	7.23	7.00
Ar	5.93	5.95	5.45	5.67	5.22		5.82	6.6	6.48
C/O	+ 0.58	+ 0.63	+ 0.46	+ 0.16	+ 0.69	- 0.88	- 0.91	- 0.25	+ 0.06
N/O	- 0.66	- 0.80	- 0.44	- 0.74	- 0.90	+ 0.32	- 1.54	- 0.93	- 0.39

TABLE 2

Adopted Logarithmic Elemental Abundances and Ratios in the

Large Magellanic Cloud on Scale log N(H) = 12.00

	LMC						LMC H II Region
	P02	P07	P09	P25	P33	P40	
He	11.05	11.21	11.24	11.05	11.09	11.00	10.93
C	8.66	7.34	7.49	7.27	8.51	8.50	8.50
N	7.56	8.30	8.26	7.67	7.77	7.15	6.98
O	8.20	7.91	7.98	8.03	8.39	8.23	8.41
Ne	7.36	7.41	7.32	7.40	7.61	7.49	7.73
S	6.51	6.58	6.70	6.43	6.59	6.38	6.96
Ar	5.99	6.11	6.19	5.98	6.15	6.07	6.24
C/O	+ 0.46	- 0.57	- 0.49	- 0.76	+ 0.12	+ 0.27	- 0.51
N/O	- 0.64	+ 0.39	+ 0.28	- 0.36	- 0.62	- 1.08	- 1.08

C Data for H II regions in both SMC and LMC are from Dufour, Shields, and Talbot (1982); for other elements data are from this source and Aller, Keyes, and Czyzak (1979).

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